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Flash x-ray imaging of kraft black liquor sprays

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ABSTRACT

The requirements for an optimal black liquor spraying system are unique among combustion processes with respect to the high flowrates and large droplet sizes required. The study of such large and coarse sprays is difficult via usual optical imaging techniques. Flash X-ray Radiography (FXR) is a unique and powerful tool for investigating high speed multiphase flows in general and kraft black liquor sprays in particular. This paper describes the imaging technique and discusses its application to the problem of kraft black liquor sprays.

The need for black liquor delivery systems research

One of the most significant problems faced by the kraft industry today is the capital intensiveness of its process technology, especially the recovery boiler. Thus, there is a tremendous incentive for increasing the production capacity of existing units.

The limit on production capacity of most kraft recovery boilers is the rate of plugging of the convective passages by excessive carryover of partially burned black liquor particles and excessive sulfur release coupled with low fuming. Thus the need exists to develop new black liquor delivery systems which permit increased processing rates without increased carryover. This involves a delicate balance, as liquor droplets which are too coarse and wet will reach the bed and cool it while droplets which are too fine lead to excessive carryover.

In addition to simple carryover, recent work (1,2) has shown that particle size is one of the most important variables in kraft black liquor burning.

These studies have shown that both volatiles burning rate and sulfur emissions significantly increase with decreasing droplet size. Since volatiles burning is closely tied to particle swelling, a high burning rate will increase swollen volume and likelihood of entrainment. The higher proportional sulfur release from small particles will produce difficult to remove deposits unless higher fume quantities are also produced. Droplets which are too large can reach the bed wet to cause furnace instabilities and blackouts. Entering black liquor droplet size distribution is therefore one of the most important parameters to measure and control.

While the importance of black liquor droplet size distribution has become understood during the last decade, it is a fact that commercial spray nozzles have remained essentially unchanged. Research directed at developing new black liquor delivery systems (nozzles) capable of producing well-defined droplet size distributions would seem appropriate at this time.

Comparison with other spraying systems

Literally dozens of investigations (3) of various spraying systems have been carried out primarily in the areas of fuel combustion and spray drying. Typical spray characteristics for each of these are listed in Table 1. Recovery boiler spray nozzles are clearly unique among fuel delivery systems both in terms of desired droplet size and flowrate.

Table 1 here

The high flowrate and coarse average droplet size lead to difficulties in studying such large sprays via optical means.

Previous work

No results have been published regarding the performance of commercial sprays of kraft black liquor at operating temperatures. Stockel (4) has investigated the single jet breakup of model fluids and weak black liquor with vibratory assist. Bennington and Kerekes (5) have compared small scale sprays of concentrated black liquor and model fluids. Both investigations employed traditional optical imaging techniques.

Such techniques are severely limited when applied to large scale sprays. To overcome problems of depth of field very long focal length lenses must be employed. Desired resolution is achieved by investigating only small portions of the spray. One must question the statistical significance and ease of application of a technique capable of investigating only a few square centimeters of a spray covering several square meters.

Flash X-ray Radiography

Flash X-ray Radiography (FXR) is a powerful technique for the investigation of high speed multiphase flows which offers some unique advantages over optical systems when attempting to image large sprays with broad droplet size distributions.

Practical FXR systems

Modern FXR systems employ intense x-ray bursts of 10-100 nanoseconds in duration and energy levels up to several MeV to image high speed events which are optically thick. FXR has been traditionally used by the various weapons laboratories (6,7) to image ballistic events. One application to fine sprays can be found (8). The technique was recently (9) applied to the problem of imaging high speed flows of concentrated fiber suspensions.

Several excellent texts exist (10-12) which describe the FXR technique in detail. All FXR systems comprise three components:

- A pulsed power supply capable of delivering very short, high voltage, high current electrical pulses to some x-ray generator.
- An x-ray generator to transform the electrical pulse into an intense x-ray pulse which can be used for imaging purposes.
- Some x-ray detector system to convert spatial variations in x-ray intensity to some form of usable (visual) image.

FXR power supplies usually take the form of Marx-Surge generators or pulse transformers. The former typically deliver 30-70 nanosecond pulses in the 0.15 to 2.5 MeV range at current levels on the order of 10^4 A. While pulse transformers operate at the lower end of this range, they do offer the possibility of high repetition rates (10^4 pulses per second) while M-S generators are essentially single flash devices.

All practical x-ray generators currently in use are of the field emission type. A common design is shown in Fig. 1. Under sufficiently high applied voltages (10^7 - 10^8 V/cm) electrons leave the cathode and bombard the anode, resulting in the emission of a short burst of Bremsstrahlung x-rays. FXR system resolution is essentially determined by source size and geometrical arrangement as shown in Fig. 2.

Figures 1 and 2 here

High speed industrial x-ray films are the least expensive and highest resolution x-ray detectors available. Fluorescent screens and image intensifiers can be used to improve sensitivity (penetration), but resolution is lost in both cases.

Several FXR systems are listed in Table 2. Those highlighted with an asterisk are part of a unique FXR laboratory at The Institute of Paper Chemistry.

Table 2 here

FXR system performance

The ability of two commercial FXR systems to penetrate air and water are shown in Fig. 3 and 4. Also shown are the x-ray doses required to directly expose several commercial films to optical density = 1. By employing fluorescent screens the required dose can be reduced several orders of magnitude. However, direct exposure is best for high resolution work.

Figures 3 and 4 here

Advantages with respect to optical systems

Speed is not an issue when applying FXR techniques to high speed flows. Although 10^{-8} s optical exposure times are possible with pulsed lasers, FXR systems are much easier to implement. As shown in Fig. 2, FXR produces a simple shadow graph. There is no "depth of field" concern. Most significantly, FXR can easily image a 1 x 1 m object with 100 μ m resolution throughout the field of view. These characteristics give FXR several general advantages relative to optical imaging methods.

Applications of FXR to black liquor sprays

Figures 5, 6, 7, and 8 are FXR images of heavy black liquor sprays taken with system 2 of Table 2 at conditions shown in Table 3. This technique offers several additional advantages relative to optical techniques in these cases. Steam present when spraying near the fluid's normal boiling point is transparent

to x-rays. FXR can see through the spray to clearly show the simultaneous occurrence of sheets, filaments, and droplets. Finally, image gray levels can be correlated with sheet thickness to give mass distribution.

Figures 5, 6, 7, 8, and Table 3 here

Conclusions and future work

FXR has demonstrated a unique capability to image large scale commercial black liquor sprays at normal operating conditions. Most important of its advantages is the ability to image large fields of view with fine resolution and to see through complex sprays.

One problem requires attention. The finite size of any practical FXR source causes some image blur. This can be minimized by maximizing source to film distance. The problem may also be eliminated via digital image processing.

At this time a unique facility is under construction to allow the systematic investigation of large black liquor sprays via FXR. Early studies will include the effects of black liquor concentration, temperature and flowrate on droplet size distribution from current commercial spray nozzles.

ACKNOWLEDGMENTS

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Table 1. Desired spray characteristics.

	Black Liquor	Fuel Oil	Spray Drying
Average droplet diameter, mm	2-4	0.01-0.05	0.01-1.0
Flowrate ($\text{m}^3/\text{s} \times 10^3$)	1-8	0.1-1	1-10

Table 2. FXR systems.

Builder	Exposure Time (s)	Framing Rate (fps)	X-ray Spot Size (mm)	Energy (KeV)
1. *Hewlett-Packard	3×10^{-8}	0	~ 5	300
2. *Hewlett-Packard	7×10^{-8}	0	~ 1	150
3. *Lawrence Liver- more Laboratory	3×10^{-8}	0	< 0.1	150
4. Impulsphysics (GMBH)	10×10^{-8}	5×10^3	~ 1	150

Table 3. Black liquor test conditions.

FXR System - Hewlett-Packard 150 KVp -				
Film - Kodak AR-5 -				
	Fig. 5	Fig. 6	Fig. 7	Fig. 8
Source to film distance (m)	0.53	0.53	0.53	0.53
Black liquor concentration (%)	65	65	65	65
Black liquor temperature (°C)	104	104	104	111
Black liquor pressure (kPA)	157	185	241	185
Spray nozzle	- B&W No. 17 Splash Plate -			

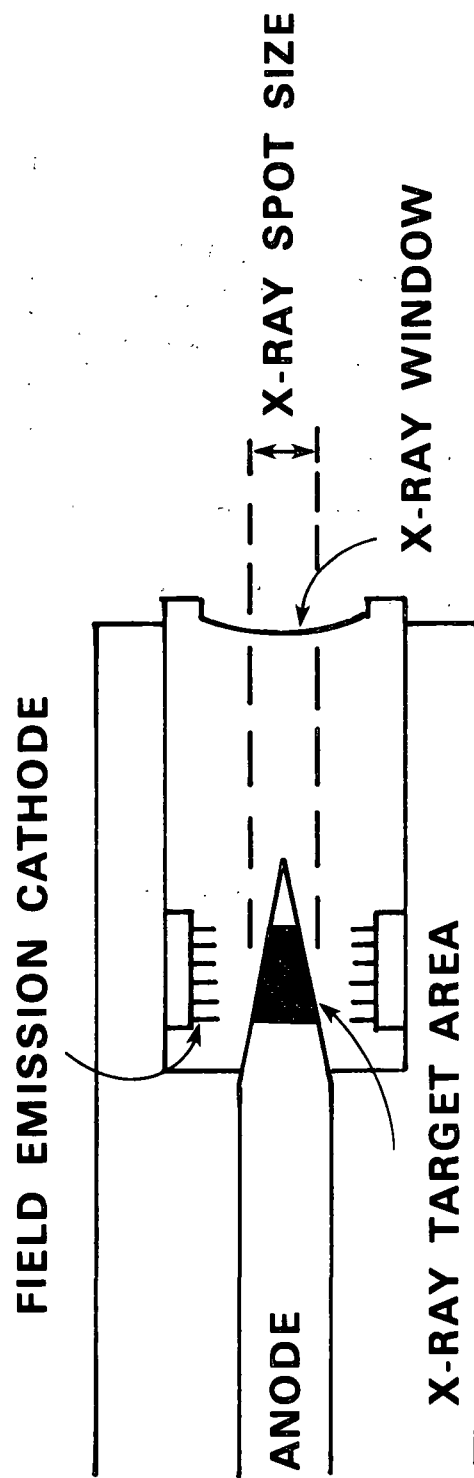


Figure 1. Common x-ray generator for FXR

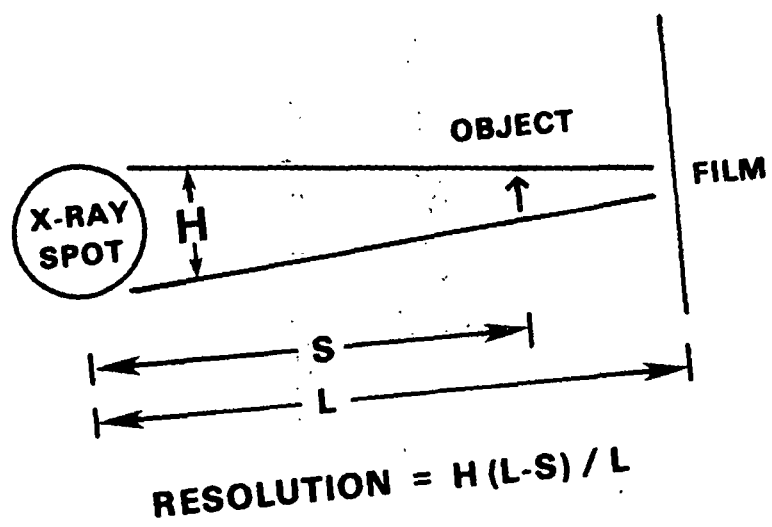


Figure 2. FXR resolution

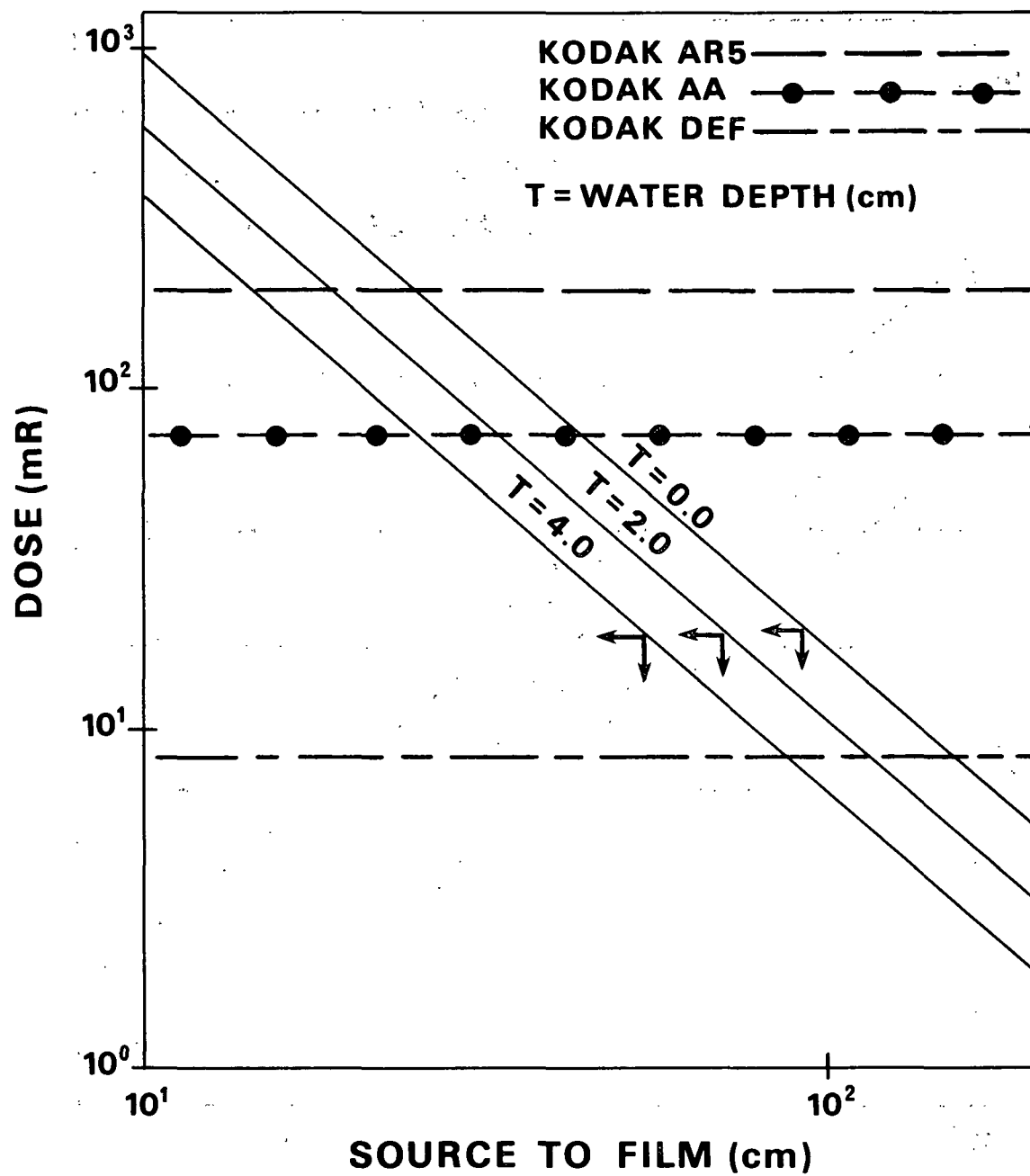


Figure 3. Performance of FXR system #1 (Table 2)

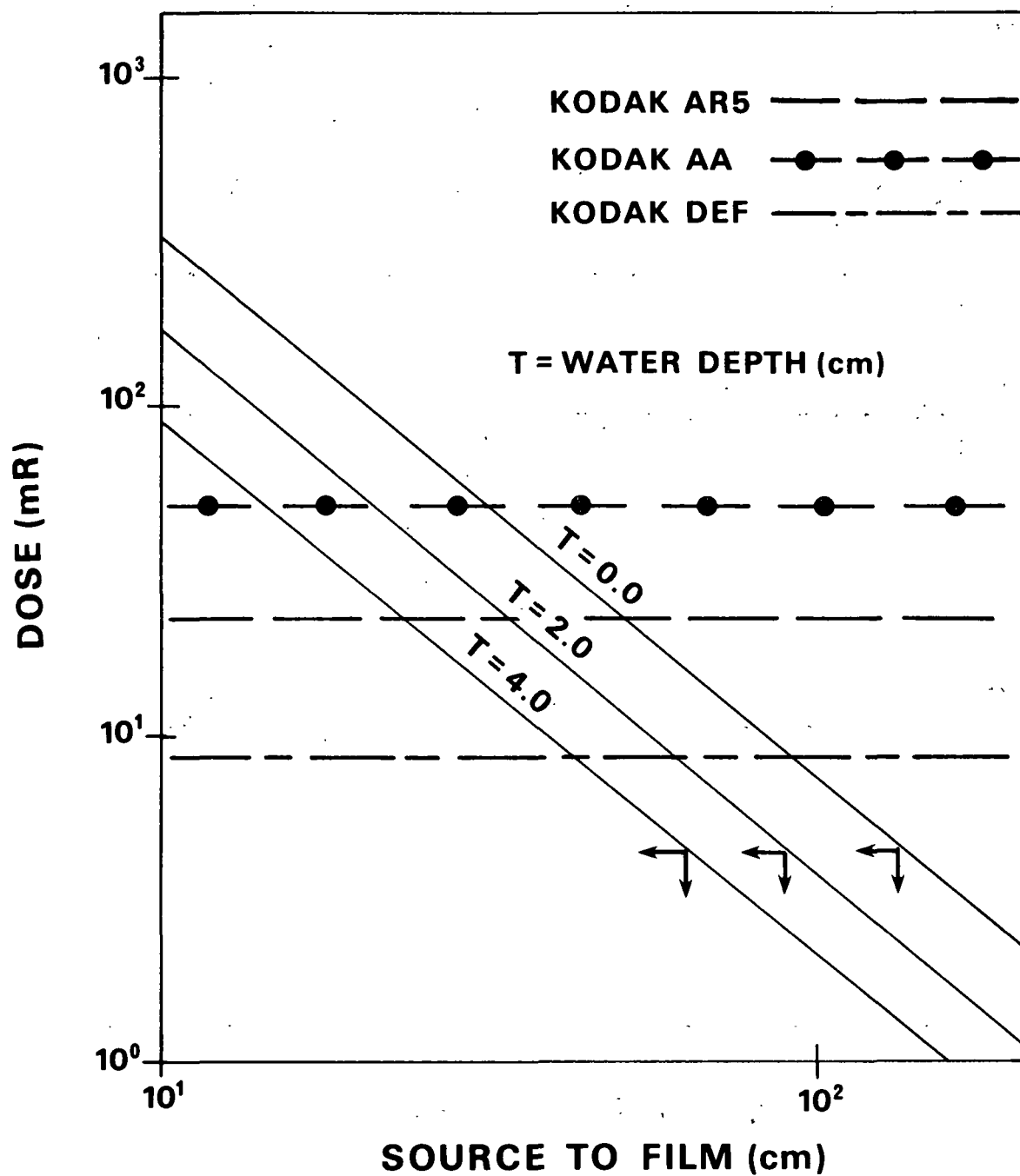


Figure 4. Performance of FXR system #2 (Table 2)

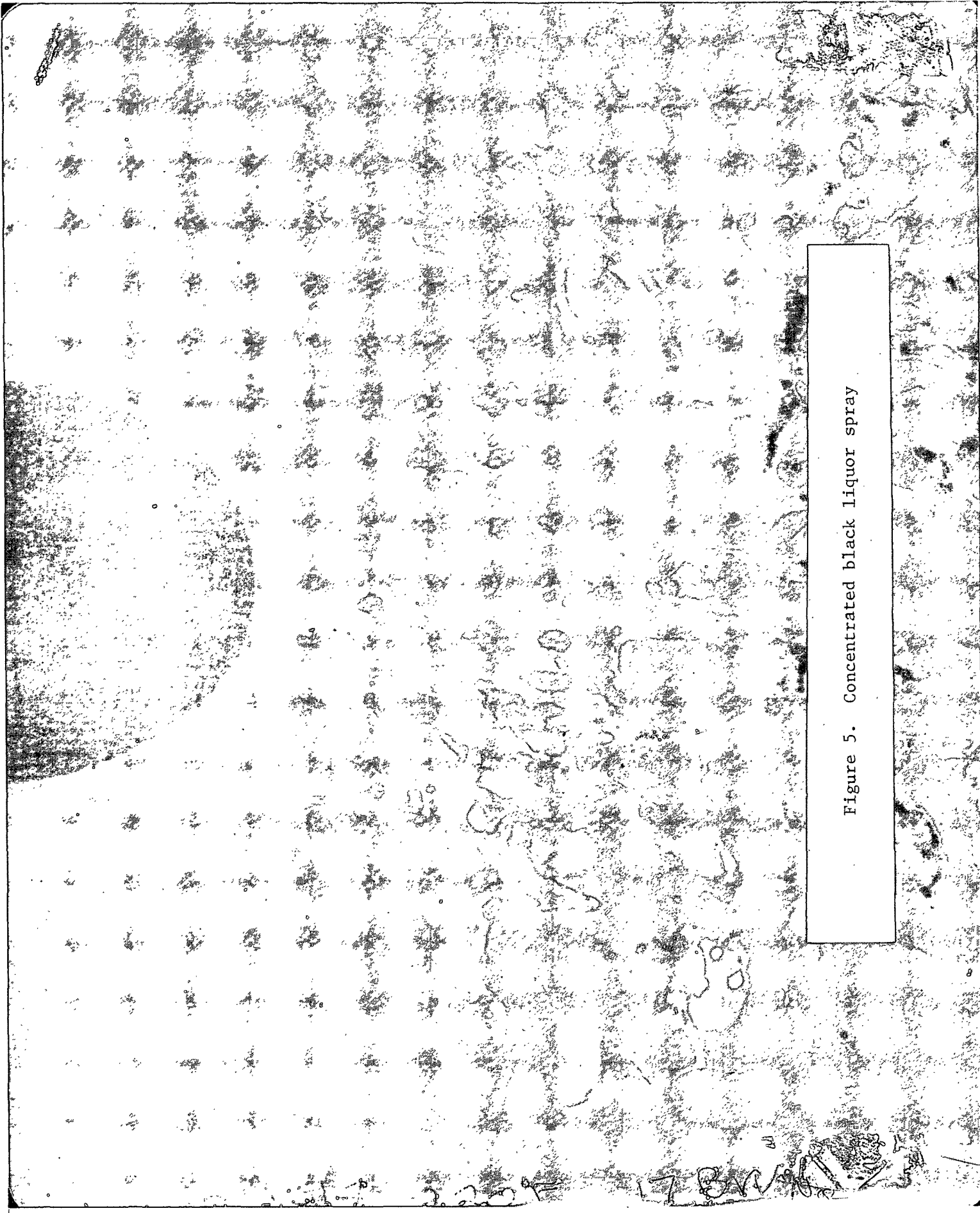


Figure 5. Concentrated black liquor spray

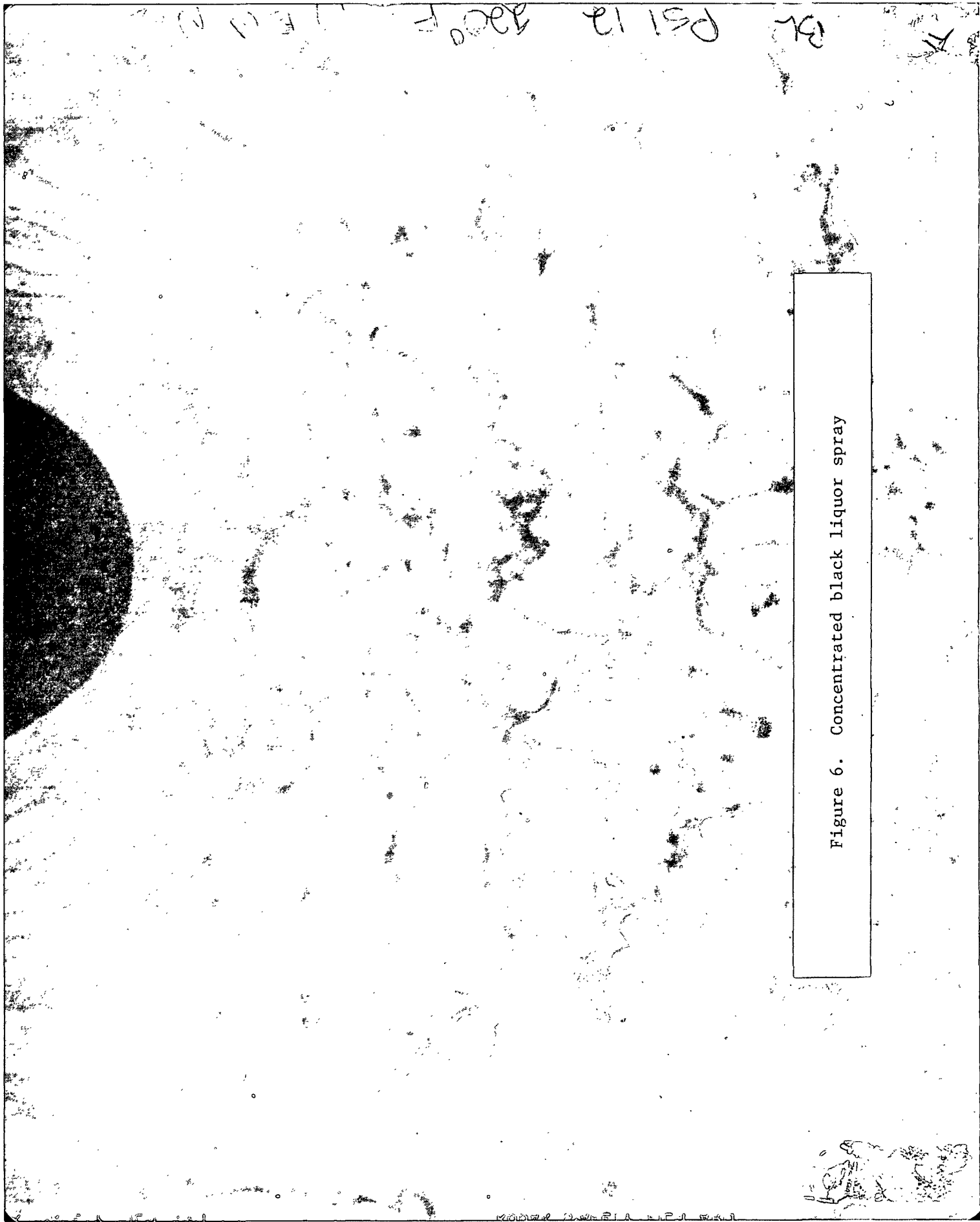


Figure 6. Concentrated black liquor spray

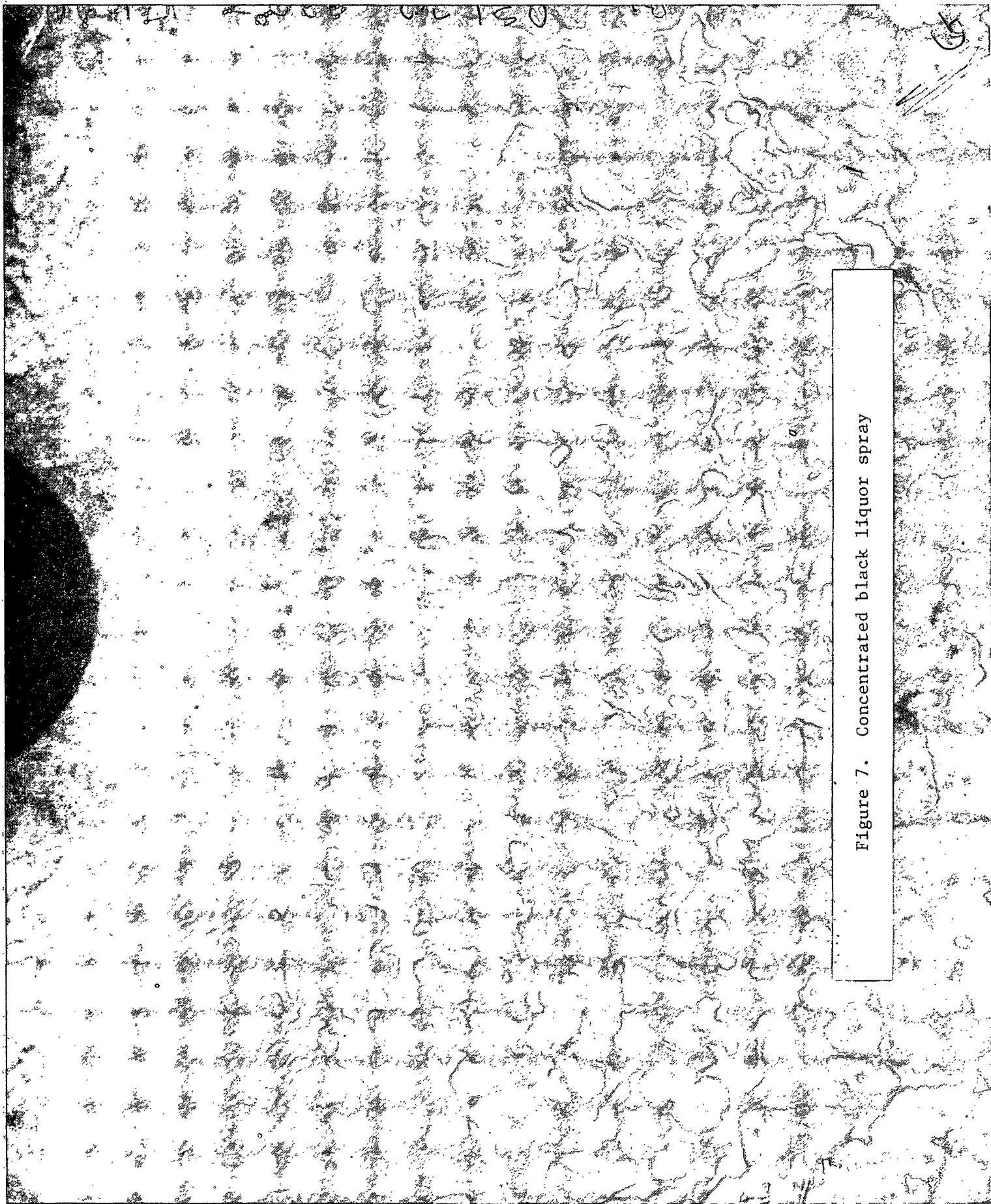


Figure 7. Concentrated black liquor spray